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The effect of UV irradiation duty cycle on the 2nd harmonic coupling efficiency in optical fiber long period gratings

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Abstract

Long period gratings (LPGs) as a sensing platform have the potential for multi-parameter sensing through the utilization of 2nd order coupling resonance bands. Although current literature has produced LPGs with 2nd order attenuation bands, the fabrication parameters required to generate these features has not been elucidated. Using UV irradiation via the point-by-point method, here it is shown that by varying the duty cycle it is possible to fabricate LPGs that exhibit 2nd, 3rd, and 4th order resonance bands. Fabrication of LPGs with a 25% or 75% duty cycle produces distinct 2nd order resonance bands, which are not observed when a 50% duty cycle is adopted.

Introduction

Optical fiber long period gratings (LPGs) have been explored widely in the literature as a transducer element for numerous physical, biological and chemical sensors [1]–[3]. Their popularity as a sensing platform has emerged due to their inherent sensitivity to strain, temperature, bending and, in particular, the refractive index of the medium surrounding the fiber. LPGs are phase gratings, typically taking the form of a periodic refractive index modulation within the core of the fiber, with a periodicity between 70 and 1000 µm. LPGs operate by coupling light from the core mode to co-propagating cladding modes producing a number of distinct resonance bands in the transmission spectrum, characterized by the phase matching expression [4],

$$\lambda(x) = \frac{(n_{core} - n_{clad(x)})\Lambda}{N}$$

where $\lambda(x)$ is the center wavelength at which coupling occurs, n_{core} is the effective refractive index of the mode propagating in the core, $n_{clad(x)}$ is the effective refractive index of linearly polarized cladding mode with an x^{th} radial order LP_{0x}, Λ is the period of the grating, and N = 1, 2, 3… is the order of diffraction.

The fabrication of LPGs is often achieved by exposing the optical fiber's core to UV irradiation, either through an amplitude mask or by utilizing the point-by-point method. Although the former allows for fast, easy and repeatable production of LPGs, the point-by-point method provides greater flexibility in grating design [5].

The feature-rich transmission spectrum of an LPG has the potential to be exploited for multi-parameter sensing, where the different sensitivities of the resonance bands that correspond to distinct cladding modes allow the influence of different physical parameters to be separated. For example, it has been shown that it is possible to measure simultaneously bending and temperature [6], [7] and temperature and strain [8]. To ensure sufficient discrimination of the parameters, the orders of the cladding modes corresponding to the resonance bands should be widely separated, requiring a large wavelength range for this to be achieved.

Multi-parameter sensing can also be performed through the utilization of 2nd order coupling features. In [9] it was shown that the use of 1st and 2nd order resonance bands can allow the separation of temperature and strain responses. The resonance bands corresponding to the 1st and

2^{nd} order coupling were in distinct wavelength bands, 1523.0 and 761.5 nm respectively for LP_{07} mode. James *et al.* [4] showed that it is possible to observe 2^{nd} order coupling resonance bands that occupy the same spectral region as those corresponding to 1^{st} order coupling, allowing the distinction between temperature and surrounding refractive index to be discerned over a narrower wavelength range thus allowing the LPG to be analyzed using a single source and interrogator. Furthermore, the 2^{nd} order features corresponded to higher order cladding modes which were operating near their phase matching turning point (PMTP), where their sensitivity to environmental changes is at its maximum [10]. In this case it was shown that the response of the 2^{nd} order bands to changes in the thickness of a coating was significantly larger than that of the 1^{st} order resonance bands. However, in both of these reports, there was no discussion of how the 2^{nd} order coupling features were generated.

To date, there has been little in the literature of LPGs that discusses the optimum grating profile for the generation of higher order coupling effects. Often the higher order coupling effects are seen as a hindrance and techniques have been developed to avoid producing harmonic resonances in LPG transmission spectra [11]. Nevertheless, Barrington *et al.* [12] showed that, with appropriate grating design, resonance bands corresponding to 1^{st} and 2^{nd} order coupling may be observed within a relativity small wavelength range (~100 nm), with both orders operating near their PMTP. Although the periodicity of the LPG determines the wavelength at which light is coupled to a cladding mode, the manufacturing process required to generate LPGs with optimized harmonic resonance bands has not been explored.

The fabrication of LPGs via UV exposure, whether through an amplitude mask or using the point-by-point method, results in the fiber being exposed to an irradiation pattern that closely resembles a square-wave [11], where its duty cycle describes the ratio of the portion of fiber exposed to UV irradiation to that which was not exposed. There has been little research conducted on assessing the effect of varying duty cycle when creating LPGs. Indeed, throughout the literature, a 50% duty cycle (where 50% of the period is exposed to UV irradiation) is commonly selected for LPG fabrication for a given period as this ratio, although it is rarely stated, has been previously shown to produce the greatest extinction in 1^{st} order attenuation bands [13]. However, it is well known that even ordered harmonics are not present in the Fourier series of a square wave with a 50% duty cycle, therefore it is expected that resonance bands corresponding to these coupling orders are not present within the transmission spectrum of an LPG with this duty cycle.

While the current literature utilizing 2^{nd} order attenuation bands demonstrates that LPGs have the potential for highly-sensitive multi-parameter sensing, it is evident that the fabrication parameters required to reliably generate these features is not fully understood. Therefore, to ensure further development of novel multi-parameter sensing applications using LPGs with 2^{nd} order resonance bands, fundamental knowledge of the fabrication parameters which govern the generation of 2^{nd} order features is required. Underpinned by Fourier series modeling of a square wave, the evolution of an LPG transmission spectrum is studied during UV point-by-point fabrication as the duty cycle is varied, with the aim of establishing a means for optimizing the extinction of 2^{nd} order coupling resonance bands.

Methods and Materials

Fourier series of a square wave

To assess the effect of duty cycle on the harmonic coupling generation from an LPG, a discrete Fourier transform was applied to the square waveform and harmonic intensity plotted as a function of duty cycle (Fig. 1). It can be seen from Fig. 1 that a 50% duty cycle would produce optimal coupling efficiency to 1st and 3rd order harmonics. Additionally, Fig. 1 indicates that gratings produced using square wave irradiation can also couple to 2nd order harmonics by using a duty cycle centered around 25% or 75%. Coupling to 2nd order harmonics, rather than 3rd would allow for easier identification in the resulting spectrum due to greater attenuation in these bands caused by the decrease in amplitude of harmonics with increasing order (observable in Fig. 1).

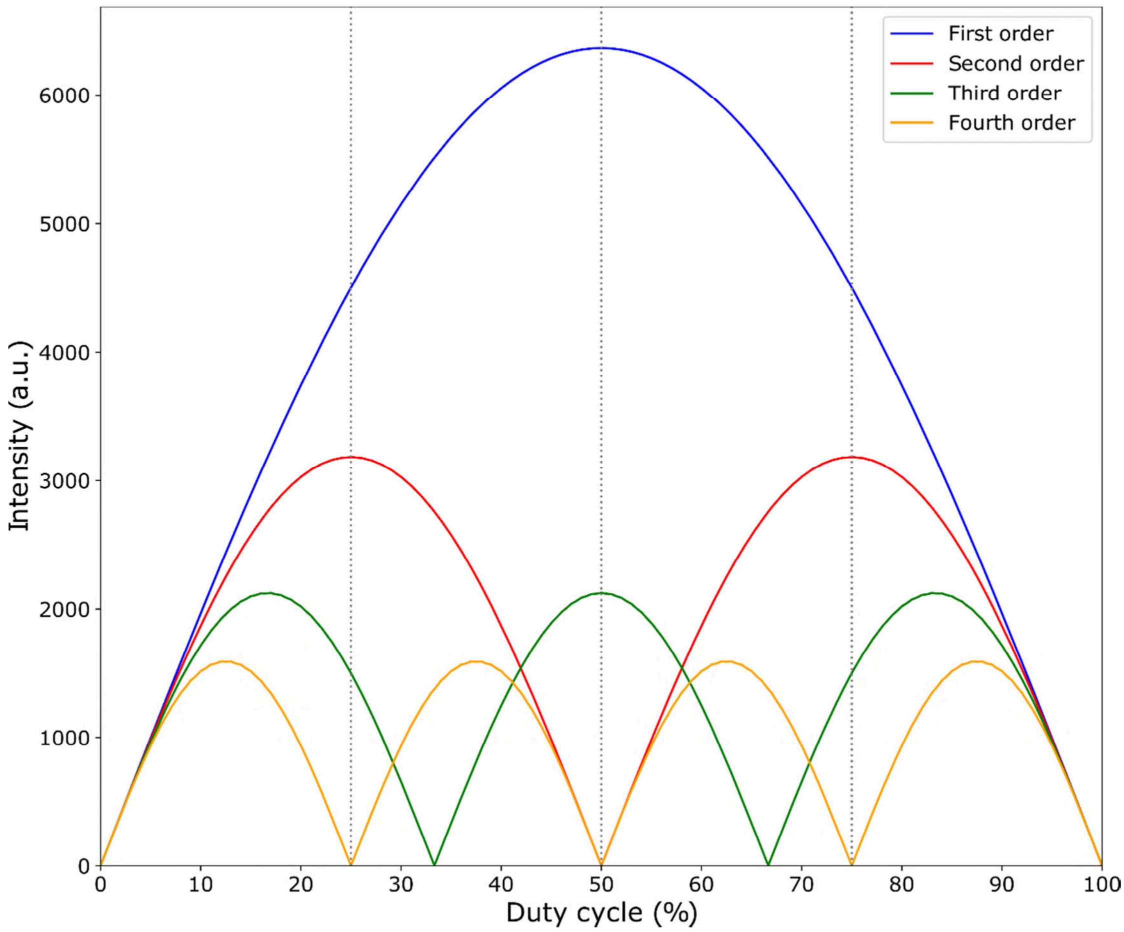

Fig. 1: Intensity of the 1st, 2nd, 3rd, and 4th harmonics present in a square wave plotted as a function of duty cycle. The vertical dotted lines act as a guide for the eye

LPG fabrication

To confirm the results presented by the Fourier analysis, an LPG of 40 mm length and a 380 µm period was fabricated using the overwrite LPG fabrication method [5]. This period was selected based on phase matching curves generated through numerical modeling [14] which showed the presence of a 2nd, 3rd, and 4th order feature coupling. Photosensitive optical fiber (PS750, Fibercore), with a cut-off wavelength of 620 nm and mode field diameter of 5 µm, was attached to a translation stage positioned behind a mechanical slit (in house design) driven by a translation stage mediated dowel (M-110.1DG, Physik Instrumente). Custom software implemented in LabView was used to control the width of the slit and the movement of the translation stage (M-150.11, Physik Instrumente), which governed the LPG's duty cycle and period, respectively. The slit was comprised of two ceramic plates spring mounted to a frame which remained in contact with the dowel. Upon initiation of the translation stage, the dowel is driven downwards, forcing the ceramic plates apart to the desired aperture. To ensure the slit reliably produced apertures required for this work, a calibration curve was generated by setting the translation stage to a range of distances and measuring the subsequent slit aperture using a light microscope (x200 magnification) with a resolution of ±2.48 µm.

The output from a 10 Hz frequency-quadrupled Nd:YAG (450 TRLi, Litron Ltd) UV laser with an average power output of 250 mW at 266 nm was focused onto the fiber to obtain a power density of 14 $mW \cdot mm^{-2}$. The transmission spectrum of the optical fiber was monitored throughout the experimental procedure using a fiber-coupled tungsten-halogen broadband light source (LS-1, Ocean Optics) and CCD spectrometer (S2000, Ocean Optics) with a resolution of 0.3 nm.

The fabrication of the LPG involved a section of the fiber of length equivalent to a 5% duty cycle (19 µm aperture width) being subjected to UV exposure for a duration of 5 s. The fiber was then translated (orthogonally with respect to the incident UV beam) by a distance equal to the period and the fiber exposed again. This was continued for the entire length of the grating (one cycle). Upon completion of the fabrication cycle, the fiber was returned to its original location and the process repeated. Following the 10th fabrication cycle, the translation stage was returned to the initial position minus a length equivalent to that of 5% of the period. The addition of an offset allowed an LPG with a duty cycle equivalent to 10% to be subsequently fabricated using the same fiber. This offset was cumulative following every 10th fabrication cycle until an LPG with a 100% duty cycle was manufactured (Fig. 2). A spectrum was recorded following each cycle, producing a total of 10 spectra for every 5% duty cycle increment.

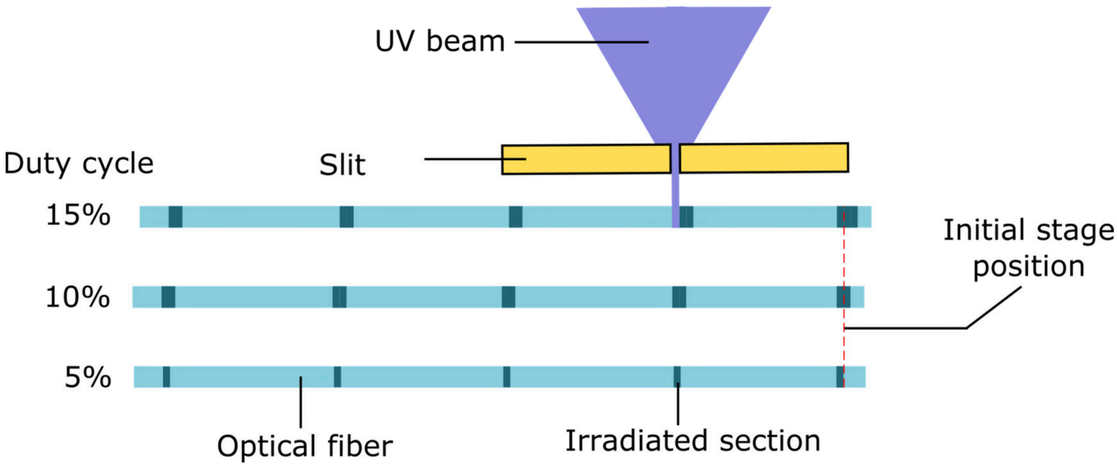

Fig. 2: Diagrammatic representation of the fabrication method used to create the single LPG. The initial stage position is labeled to emphasis the shift in stage location required to produce a cumulative duty cycle

Results and discussion

The intensity plot depicted in Fig. 3 shows the evolution of the attenuation bands in the transmission spectrum of the fabricated LPG for duty cycles from 0 - 100%, where the dark features visible depict the attenuation bands. Although 10 spectra were obtained for each increment in duty cycle, only the spectra recorded on the final fabrication step of each duty cycle were utilized in the generation of the figure.

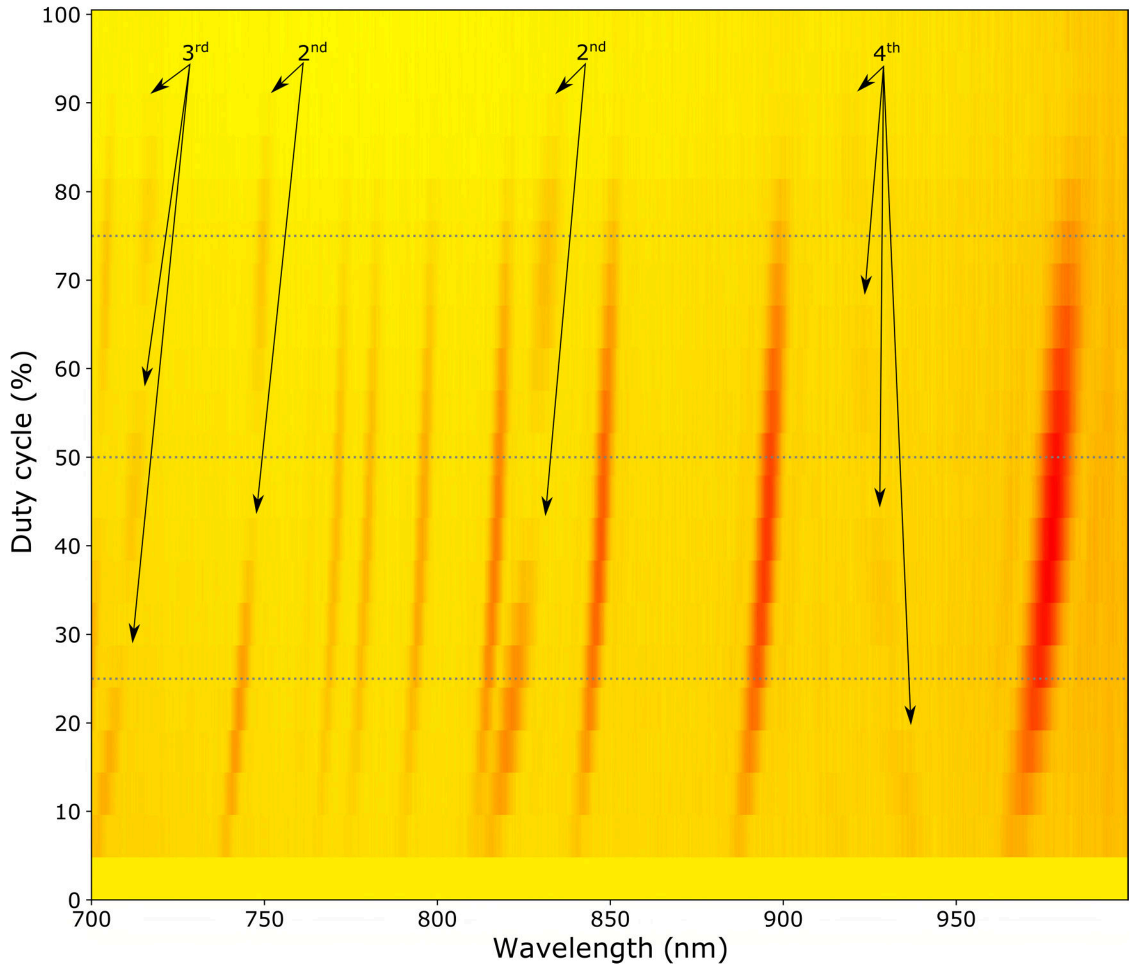

Fig. 3: Intensity plot depicting the relationship between transmission and wavelength for a 40 mm long LPG with a period of 380 μm and duty cycles between 0 - 100% for the generation of 1st, 2nd, 3rd, and 4th order harmonics. Harmonics pertaining to 2nd, 3rd, and 4th order have been labeled, all other attenuation bands are 1st order. Red and yellow correspond to 75% and 100% transmission, respectively. The horizontal dotted lines act as a guide for the eye.

It is clear from Fig. 3 that varying the duty cycle from 0 – 100% dramatically impacts the coupling efficiency of 2nd, 3rd, and 4th order harmonic features in LPGs. The bands visible between duty cycles of 5 - 90% correspond to 1st order coupling associated with cladding modes $LP_{02} – LP_{08}$, where the greatest attenuation can be seen for a duty cycle of approximately 50%. At this duty cycle, the 2nd order coupling features corresponding to LP_{12} and LP_{13} at wavelengths of 739 nm and 818 nm, respectively, are not visible. This order of coupling feature demonstrates its maximal extinction for duty cycles of centered round 25% and 75%. In addition to the 1st and 2nd order features, less intense 3rd and 4th order attenuation bands can be seen at 705 nm and 940 nm, respectively. All the observable harmonics in Fig. 3 demonstrate similar duty cycle dependence as the square wave harmonics noted in Fig. 1.

It can also be seen from Fig. 3 that the central wavelengths of the attenuation bands experience a wavelength shift throughout the fabrication procedure. This is due to the attenuation band's central wavelength being influenced by the total amplitude of the refractive index change where, in this case, the cumulative UV exposure is created from each cycle [5], [15].

Although Fig. 3 provides a clear overview to the effect of duty cycle variation, in order to identify the duty cycle at which each coupling order displayed the greatest extinction, the data utilized in Fig. 3

was re-analyzed using Spectral processing software [16] and the intensity of attenuation bands corresponding to each coupling order was plotted as a function of duty cycle (Fig. 4).

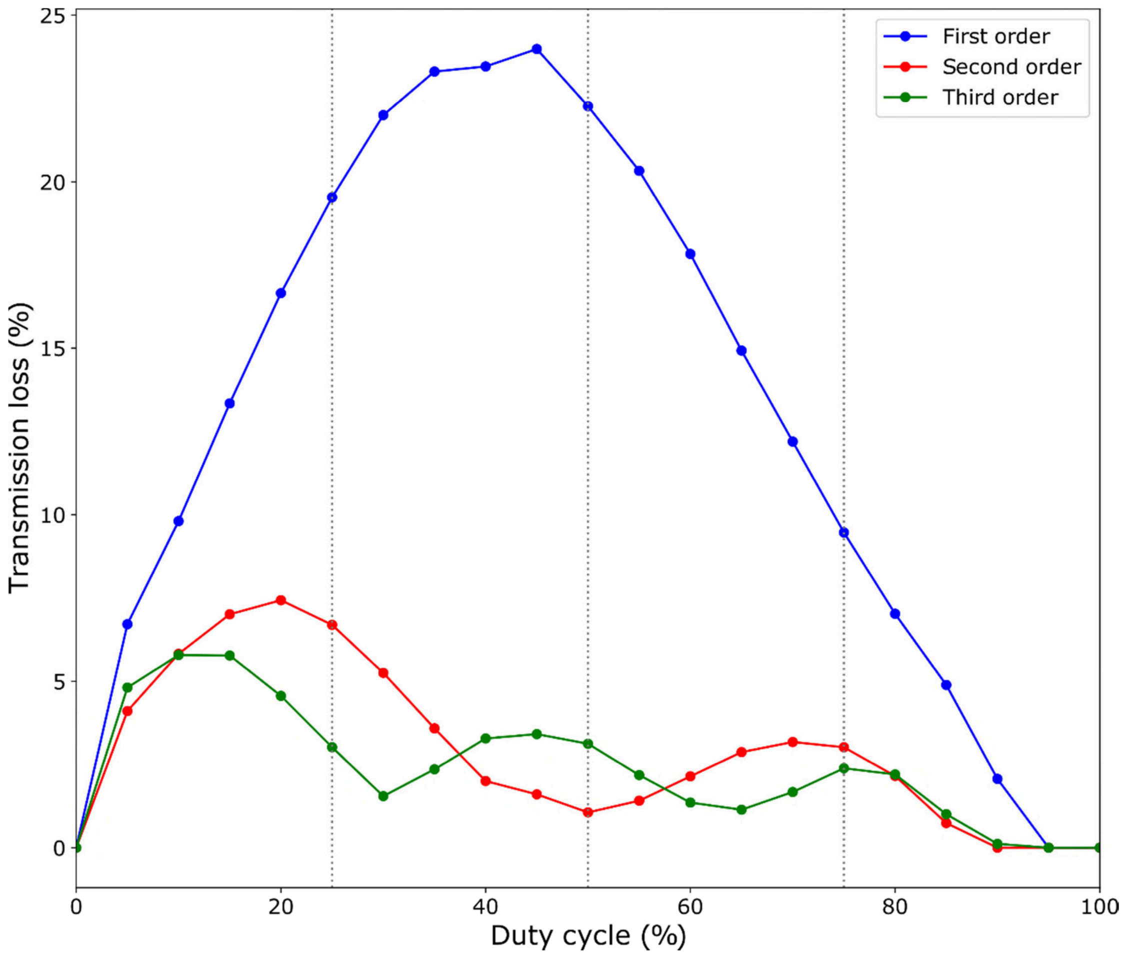

Fig. 4: The intensity change of 1st, 2nd, and 3rd order attenuation features as a function of duty cycle from the transmission spectra of a 40 mm long LPG with a period of 380 µm. The vertical dotted lines act as a guide for the eye

Fig. 4 shows that the 1st order resonance features displayed their greatest attenuation at a duty cycle of 45%. This is in disagreement with the data presented in Fig.1, which depicts the greatest attenuation of 1st order attenuation features would be fabricated at duty cycles of 50%. Furthermore, this 5% is offset is apparent for both 2nd and 3rd order features. It was expected that the maximum extinction of 2nd order features would occur at duty cycles of 25% and 75% (Fig. 1), however, as can be seen in Fig. 4, the fabricated LPG showed the largest attenuation for 2nd order features to be at 20% and 70%. This offset is most likely due to a small error in calibration of the mechanical slit used to govern the duty cycle. Since the process utilized here applied a cumulative procedure to fabricate a single LPG with duty cycles ranging from 0 - 100%, even a small discrepancy in aperture width (1 µm) would significantly impact the duty cycle following multiple 5% additions. It should also be noted that although 4th order coupling features are visible in Fig. 3, it was not possible to resolve them during the spectral analysis due their low attenuation.

Additionally, the data in Fig. 4 shows that as the duty cycle increases, the maximum attenuation decreases for both 2nd and 3rd order coupling features. This reduction in extinction is caused by a decrease in coupling efficiency between the core and cladding modes due to a greater proportion of the irradiated square wave being comprised of the DC term as the duty cycle increases. Therefore, to maximize the attenuation of higher order features, the shortest possible duty cycle should be selected (i.e. 25% rather than 75% for 2nd order coupling features).

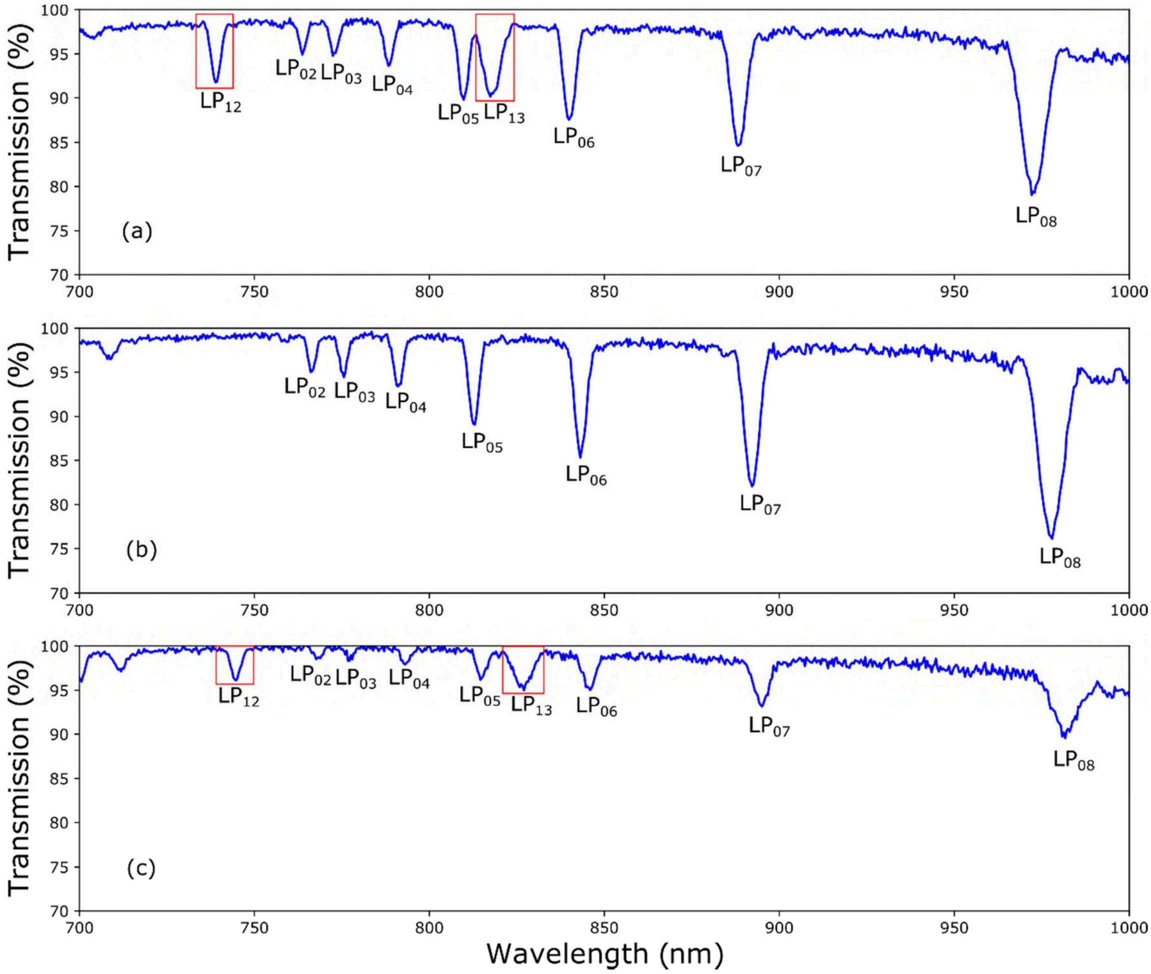

Fig. 5: Transmission spectra of a 40 mm length LPG with a period of 380 µm for duty cycles of 20% (a), 45% (b), and 70% (c). The areas highlighted indicate where the 2nd order feature is apparent for a 20% (a) and 70% (c) duty cycle and where it is not for a 45% duty cycle (b).

Since 2nd order coupling features are relevant for multi-parameter sensing, a comparison of the transmission spectra of LPGs with duty cycles that demonstrate these attenuation bands at their greatest extinction (20%, 45%, and a 70% duty cycles) can be seen in Fig. 5. The lack of a 2nd order feature in an LPG with a 45% duty cycle is apparent when compared to a grating fabricated with a 20% or 70% duty cycle (Fig. 5a). Although 2nd order harmonic resonance band are evident in Fig. 5(a), the attenuation of the 2nd order coupling features are typically lower when compared to 1st order resonance features. In a practical sense, this reduction in intensity increases the difficulty for peak tracking software to identify 2nd order attenuation bands from background noise in the transmission spectrum. This can be a particular issue for LPGs coated with specie specific depositions, often employed in chemical and biological sensing [17], [18], as the applied material can severely reduce the attenuation of the resonance features [19]. Therefore, utilizing a duty cycle that allows optimum coupling efficiency (i.e. 25%) is essential in the fabrication of LPG-based sensors. Fig. 5 also reiterates the disparity in attenuation of the resonance features as the duty cycle increases, where there is a clear decrease in extinction for all bands from Fig. 5 (a) to Fig. 5 (c).

Conclusions

In summary, the fabrication of an LPG that couples efficiently to higher order harmonics for use as a multi-parameter sensor requires consideration of the duty cycle. In order to maximize the strength of the 2nd order attenuation bands, a duty cycle of 25% should be selected. A large refractive index perturbation is required to observe clearly features associated with higher order coupling exceeding that of 2nd order.

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